NUMERICAL TESTING OF A GEOSTROPHIC DIVERGENT MODEL

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NUMERICAL TESTING OF A

GEOSTROPHIC DIVERGENT MODEL

by

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ABSTRACT

A divergent geostrophic prediction model proposed by Duthie is investigated to determine its usefulness in producing realistic forecasts and to determine the feasibility of further research using the gradient wind.

24-hour forecasts were made using the prediction equation,

$$\underbrace{\nabla^2 \frac{\partial z}{\partial t}}_{(A)} - \underbrace{\nabla \frac{\partial z}{\partial t} \cdot \nabla \ln f}_{(B)} = \underbrace{-J(z, \zeta_g)}_{(C)} + \underbrace{\zeta_g J(z, \ln f)}_{(D)}$$

at 300 mb, 500 mb, and 850 mb for summer and winter situations, with and without term B and with a tuning constant on term D.

Tables presenting the error fields for these tests are included, along with the plotted forecast and verifying maps. These tables and illustrations will show that the best results at 500 mb and 300 mb are obtained with the B term out and a tuning constant of minus four and minus one respectively on the D term. At 850 mb different tuning constants produced no significant changes in the prognostic charts.

The results of this investigation show that usable prognostic maps are produced, that the model tested has operational potentiality, and that further testing is warranted.

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TABLE OF SYMBOLS

d	the grid distance between consecutive points, 381km
D	actual height of a surface minus the standard height
f	the coriolis parameter
$\bar{f}$	the mean coriolis parameter, the value for 45N
g	the upward component of the apparent gravitational acceleration
m	the map factor
mb	millibar
S	smoothed D values
T	the twisting term, $\left(\frac{\partial \omega}{\partial y}\frac{\partial u}{\partial z} - \frac{\partial \omega}{\partial x}\frac{\partial v}{\partial z}\right)$
$\mathbb{V}$	the horizontal vector wind
$\mathbb{V}_g$	the horizontal geostrophic vector wind
ζ	the relative vorticity, $\mathbb{k} \cdot \nabla \times \mathbb{V}$
ζ_g	the geostrophic relative vorticity, $\mathbb{k} \cdot \nabla \times \mathbb{V}_g$
η	the absolute vorticity, $\eta = \zeta + f$
ω	the vertical wind component in the x,y,p,t coordinate system
J(A,B)	the horizontal Jacobian operator
$\mathcal{J}$(A,B)	the finite-difference approximation of J(A,B)
$\frac{\Delta A}{\Delta B}$	the finite-difference approximation of $\frac{\partial A}{\partial B}$
$\nabla \cdot \mathbb{V}$	the divergence of the wind
$\nabla \cdot \mathbb{V}_g$	the divergence of the geostrophic wind
∇^2	the horizontal Laplacian operator
∇^2	the finite-difference approximation of ∇^2
FNWF	Fleet Numerical Weather Facility

1. Introduction.

With the advent of the high speed digital computer, forecasting shifted from a highly subjective art accomplished by individuals using hand-drawn analyses and various prognostic methods, many of which had no theoretical foundation, to a more sophisticated method of solving the complicated differential equations governing the motions of the atmosphere. Many theoretical models have since been tested and the proficiency of the forecaster seems to have improved. However many of these models have experienced difficulty in moving troughs and systems with sufficient speed.

The purpose of this paper is to introduce a divergent geostrophic model proposed by Duthie [2]. This model allows poleward moving parcels to increase their relative vorticity and equatorward moving parcels to decrease their relative vorticity, thus allowing for development and filling. It will also move waves with a speed of the basic zonal current.

The objectives are to show that this model, which uses the divergence of the geostrophic wind, will:

a. numerically converge and produce a recognizable weather map;

b. move waves at a speed consistent with the verifying analyses;

and c. produce results sufficiently accurate to warrant further investigation.

The author wishes to express his appreciation to Professor W. D. Duthie of the U. S. Naval Postgraduate School, on whose work this paper is based, for his guidance and encouragement in this investigation. In

addition, appreciation is also expressed to the personnel of the U. S. Fleet Numerical Weather Facility for their assistance in this project. Special thanks are extended to Mr. Leo Clarke for assistance in programming and many helpful suggestions.

2. Background.

The isobaric vorticity equation for frictionless flow is [3]

$$\frac{d\eta}{dt} = -\eta \nabla \cdot \mathbb{V} + T, \tag{2.1}$$

It can be shown [1] that the divergence of the geostrophic wind is

$$\nabla \cdot \mathbb{V}_g = -\mathbb{V}_g \cdot \nabla \ln f. \tag{2.2}$$

Assuming

$$\omega \frac{\partial \zeta}{\partial p} \doteq T$$

and substituting the geostrophic divergence for the divergence in equation (2.1), the vorticity equation simplifies to

$$\frac{D}{Dt}\left(\frac{\zeta_g}{f}\right) = 0 \tag{2.3}$$

which expanded becomes

$$\frac{D\zeta_g}{Dt} = \frac{\zeta_g}{f} \frac{Df}{Dt}. \tag{2.4}$$

Equation (2.4) shows that parcels moving poleward will increase their relative vorticity and vice versa. Expanding (2.4) further gives

$$\frac{\partial \zeta_g}{\partial t} = -g f^{-1}\left[J(z, \zeta_g) - \zeta_g J\left(z, \ln f\right)\right], \tag{2.5}$$

where

$$\zeta_g = g f^{-1} \left[\nabla^2 z - \nabla z \cdot \nabla \ln f \right]. \tag{2.6}$$

Substituting (2.6) into (2.5) gives the following

$$\underset{(A)}{\nabla^2 \frac{\partial z}{\partial t}} - \underset{(B)}{\nabla \frac{\partial z}{\partial t} \cdot \nabla \ln f} = \underset{(C)}{-J(z, \zeta g)} + \underset{(D)}{\zeta g J(z, \ln f)}, \tag{2.7}$$

Equation (2.7) is a prognostic equation with a single variable, z. Term A is the local change, term B has the mathematical form of the Helmholtz term but with variable coefficients, term C is the advective term, and term D is the β term whose sign and magnitude now depend on the relative vorticity.

It is proposed to test equation (2.7) with and without term B and with a tuning constant on term D.

A basic linearized expression can be derived for equation (2.3). Assuming only a basic zonal current U and that products of perturbations are small and can be ignored, equation (2.3) becomes

$$\frac{\partial \zeta'}{\partial t} + U \frac{\partial \zeta'}{\partial x} + v' \beta = v' \beta . \tag{2.8}$$

Now assuming a solution of the form

$$\zeta = \zeta_0 e^{iu(x-ct)},$$

equation (2.8) reduces to

$$c = U .$$

This shows that waves will travel with the speed of the basic current. This analysis shows that this model should move waves faster than models whose waves move with the speed of the Rossby waves [3],

$$c = U - \frac{\beta L^2}{4\pi^2} .$$

3. Procedure.

Data for 850, 300, and 500 mb were obtained from Fleet Numerical Weather Facility, Monterey, California, for summer and winter situations. These data had been smoothed using a 15- pass, 5-point smoother over a 3969-point grid (grid distance equal to 381 km at 60N) using equation (3.1).

$$S = D + k\nabla^2 D, \tag{3.1}$$

where k is a constant smoothing factor.

Using this smoothed field, equation (2.7) becomes

$$\nabla^2 \frac{\partial S}{\partial t} - \nabla \frac{\partial S}{\partial t} \cdot \nabla \ln f = -J(S, \zeta_g) + \zeta_g J(S, \ln f),$$

which after applying finite-difference approximations [5], becomes

$$[\nabla^2 - (\nabla \ln f \cdot \nabla)] \frac{\Delta S}{\Delta t} = -\tfrac{1}{4} J(S, \zeta_g) + \tfrac{\zeta_g}{4} J(S, \ln f), \tag{3.2}$$

where $\zeta_g = \frac{g}{f} \frac{m^2}{d^2} [\nabla^2 S - \nabla S \cdot \nabla \ln f]$.

Equation (3.2) was programmed for the CDC 1604 computer using a symbolic coded relocatable assembly program (SCRAP).

The equation was solved for ΔS and then time stepped in increments of one hour using a forward time difference (3.3) the first hour and centered time differences (3.4) for succeeding hours.

$$S_{t+1} = S_t + \Delta S, \tag{3.3}$$

$$S_{t+1} = S_{t-1} + 2\Delta S. \tag{3.4}$$

At the end of 24 hours a prognostic map was plotted along with the

current analysis. From these two fields an error field was determined and from this error field a pillow (3.5) and RMSE (3.6)were computed for all points north of the equator.

$$\text{Pillow} = \frac{\sum_{1}^{N} (A - B)}{N} \tag{3.5}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{1}^{N} [(A-B) - \text{Pillow}]^2}{N}} \tag{3.6}$$

A represents the prognostic field, B the verifying field, and N the number of points used.

4. Results.

Table 4.1 lists the pillow and the RMSE for tests run with the B term of equation (2.7) in and out for summer and winter situations. All runs were for 24 hours. This table shows that the B term tends to increase the error.

Figure 4.1 is the prognostic map with the B term in. Superimposed on this map in dashed lines are the major troughs and centers of the prognostic map with the B term out (fig.4.2). Analysis of this map shows that the B term does not affect the movement of the waves but rather the intensity of the systems. The B term deepens lows and troughs and builds highs and ridges. The high over Northern Russia is 5349m with the B term in and 5321m with the B term out. It verifies as 5250m. The low over Greenland, Northern Canada, and the North Pacific covers a much broader area and is more intense with the B term in than the same low produced with the B term out. The verifying low is in better agreement with the low shown on the map with the B term out.

Another matter which must be considered is the solution time on the computer. With the B term in, it takes 105 seconds to solve the equation for one hour, 90 seconds of which is used to relax the "Helmholtz" term while it takes only 35 seconds to solve the equation with the B term out, 20 seconds of which is used in relaxation. Time on a computer is a premium and must be considered in any model.

Figure 4.2 is the prognostic map with the B term out. Superimposed on this map are the major troughs and centers of the verifying map (fig.4.3). Analysis shows that this model moves the waves faster than

B in vs B out

500 mb

	Winter		Summer	
Model	P	RMSE	P	RMSE
B in	-11'	266'	0'	102'
B out	1'	212'	-2'	93'

Table 4.1 RMSE Values for B term in vs. B term out, 500 mb

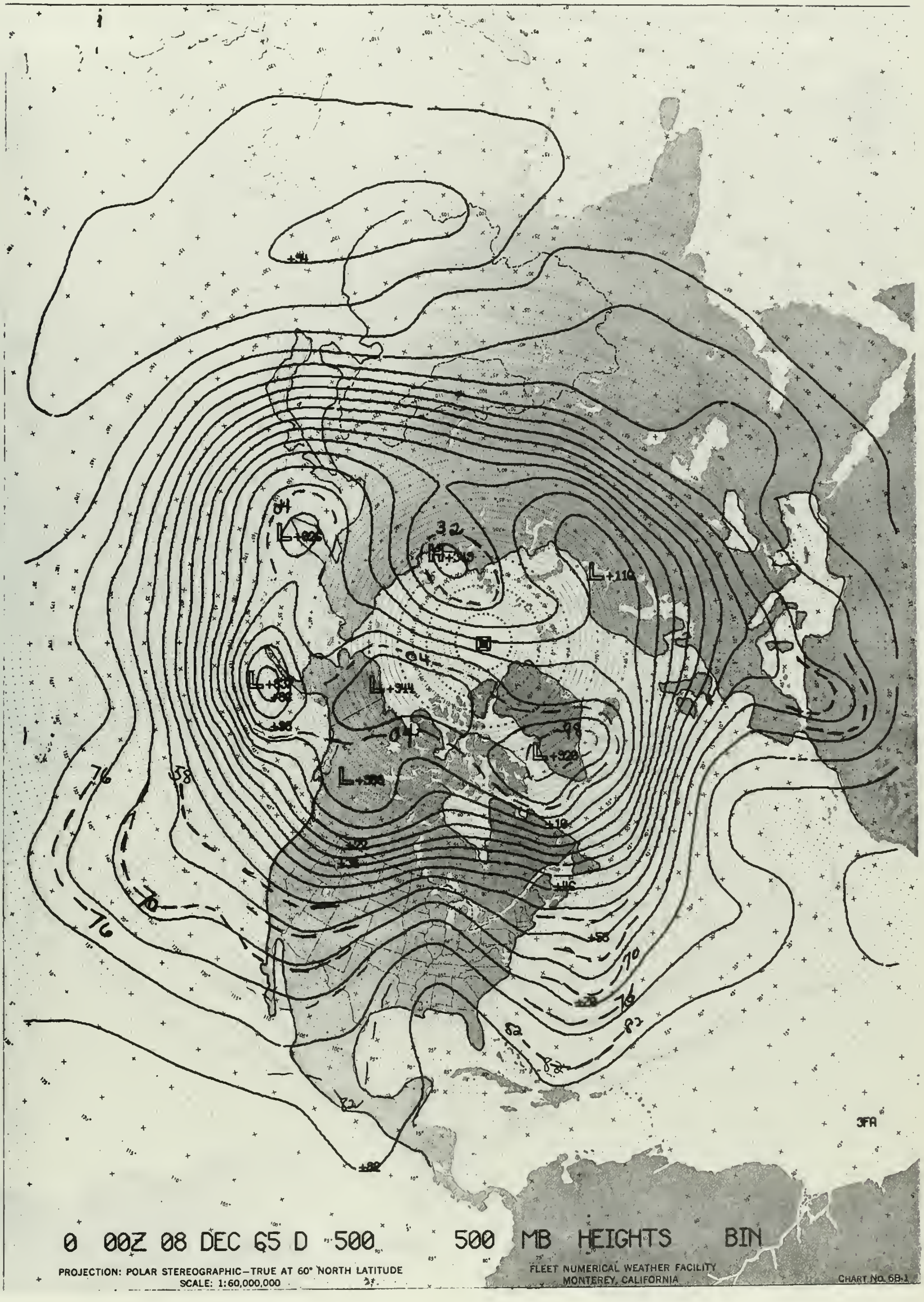

Figure 4.1 24-hour forecast for 500 mb from 8 December 1965, B term in

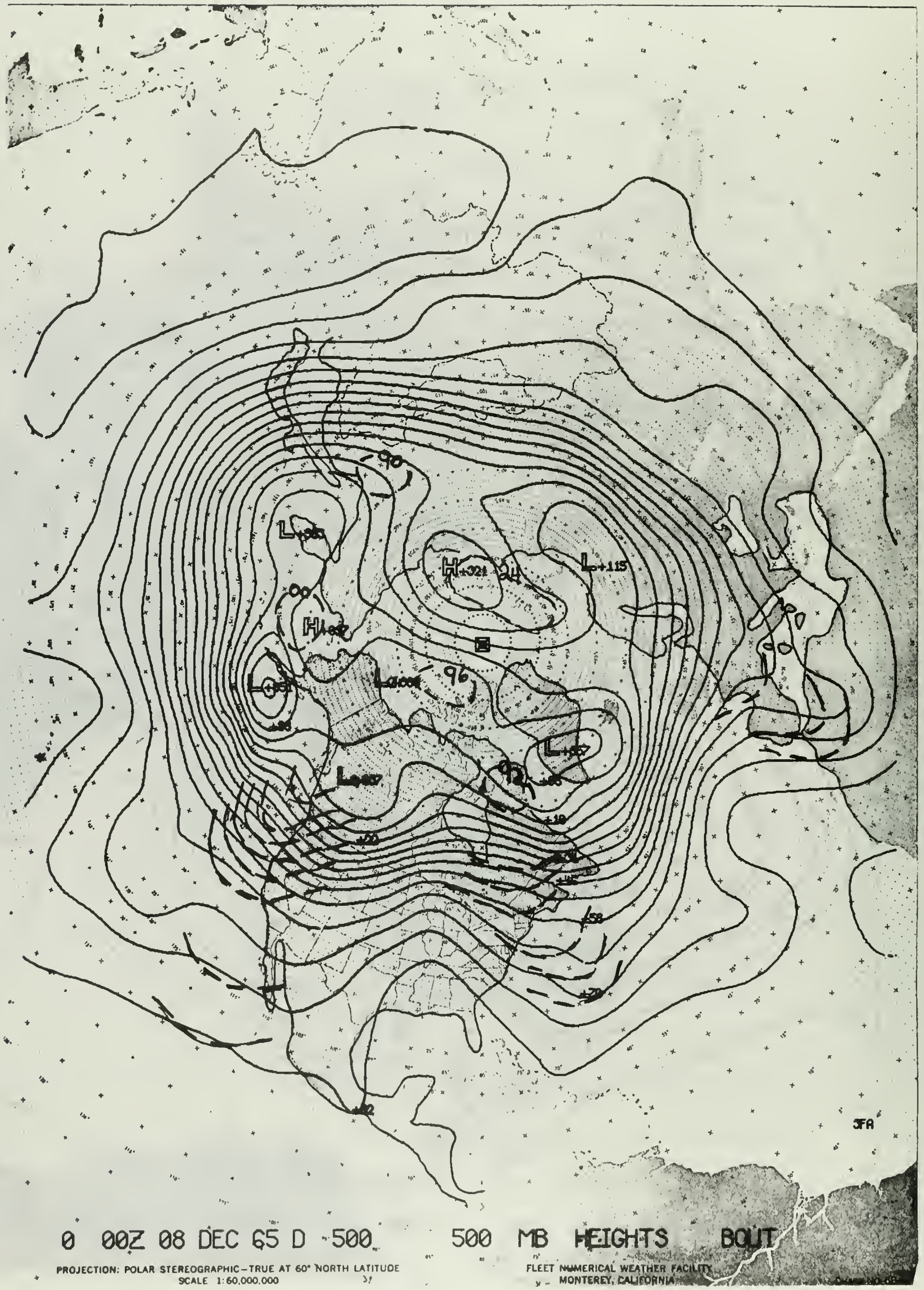

Figure 4.2 24-hour forecast for 500 mb from 8 December 1965, B term out

Figure 4.3 500-mb analysis, 9 December 1965

their verifying speeds. Centers also move too fast and are in general too intense.

Recalling that in the perturbation equation (2.8), the β terms cancelled each other and thus resulted in the waves moving with a speed equal to the zonal wind, it was felt that by changing the sign of the β term in our model (D term) we would put some of the β effect back in and slow the waves down.

Table 4.2 lists the error fields for summer and winter situations at 500 mb. This table shows that with a tuning constant of minus 4 on the D term, the model produces the best results.

Figure 4.4 is the prognostic map with the B term out and a tuning constant of minus 4 on the D term. Superimposed in dashed lines are the major troughs and centers of the verifying map.

Analysis of this map shows that the waves have slowed and now move with a speed consistent with the verifying waves. The centers appear to be in quite good agreement both in location and in intensity. It was found that increasing the tuning constant resulted in continued slowing of the waves.

It must be remembered that the verifying maps are prejudiced by FNWF's prognostic model since this is used as a first guess to the verifying data. Therefore in sparse data areas (mostly open oceans) and wherever questionable data are received, the prognostic data are used.

Figure 4.5 is a 500-mb prognostic map for summer with the B term out and a tuning constant of minus 4 on the D term. Figure 4.6 is the verifying map. Of interest in comparing these maps is the agreement on the trough coming out of the 5426m low east of Greenland and extending

B term out

500 mb

Tuning Constant	Winter: 8 Dec P	8 Dec RMSE	11 Dec P	11 Dec RMSE	Summer: 3 July P	3 July RMSE	10 July P	10 July RMSE
1	1'	212'	9'	211'	-2'	93'	0'	80'
-1	0'	160'	6'	176'	-2'	87'	-1'	76'
-2	2'	137'	4'	164'	-2'	84'	-1'	74'
-4	3'	107'	-1'	160'	-3'	81'	0'	72'
-8	7'	115'			-4'	90'	30'	140'

Table 4.2 Results of RMSE vs. tuning constant for 500 mb, B term out

Figure 4.4 24-hour forecast for 500 mb from 8 December 1965, B term out; tuning constant minus 4

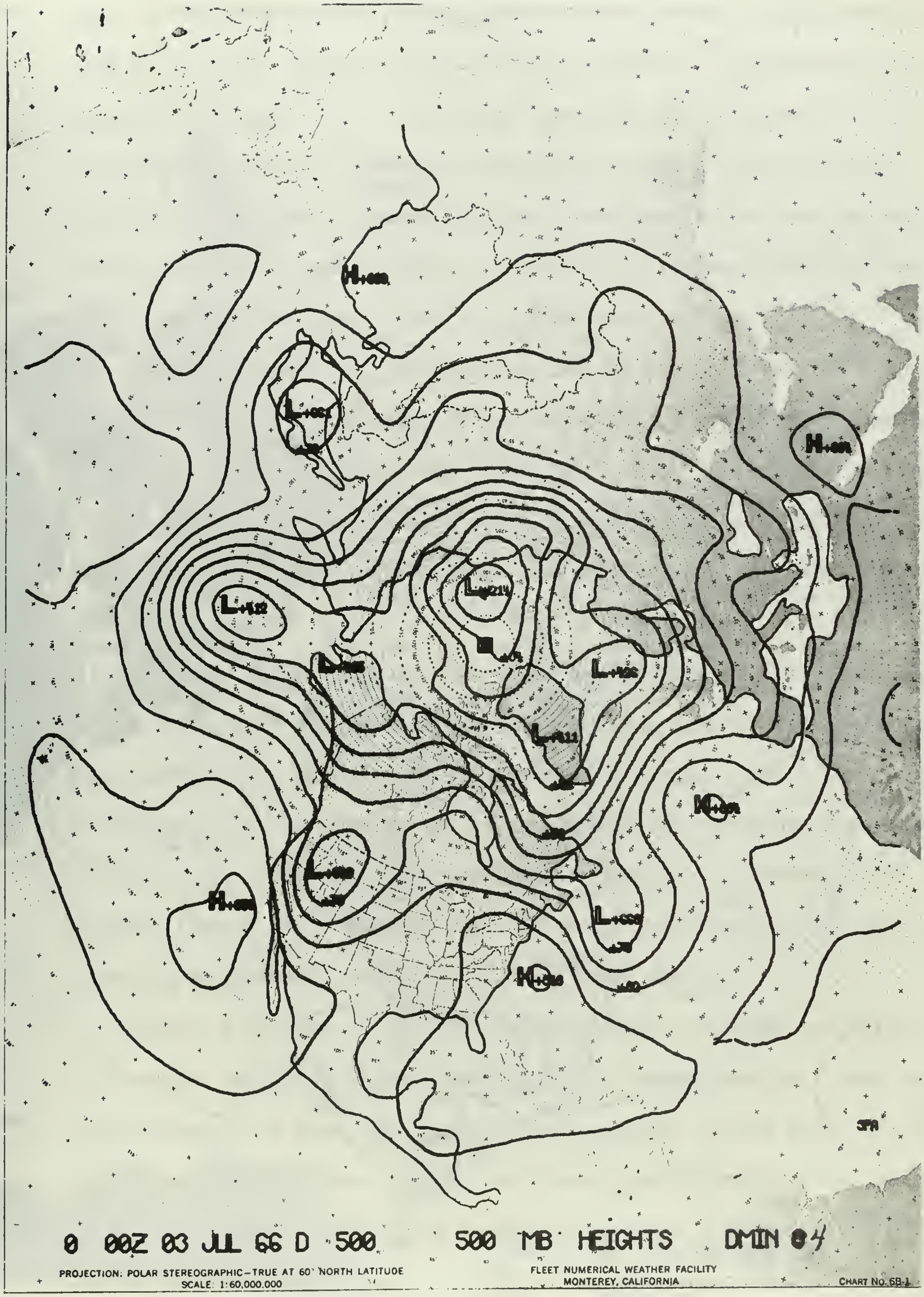

Figure 4.5 24-hour forecast for 500 mb from 3 July 1966, B term out; tuning constant minus 4

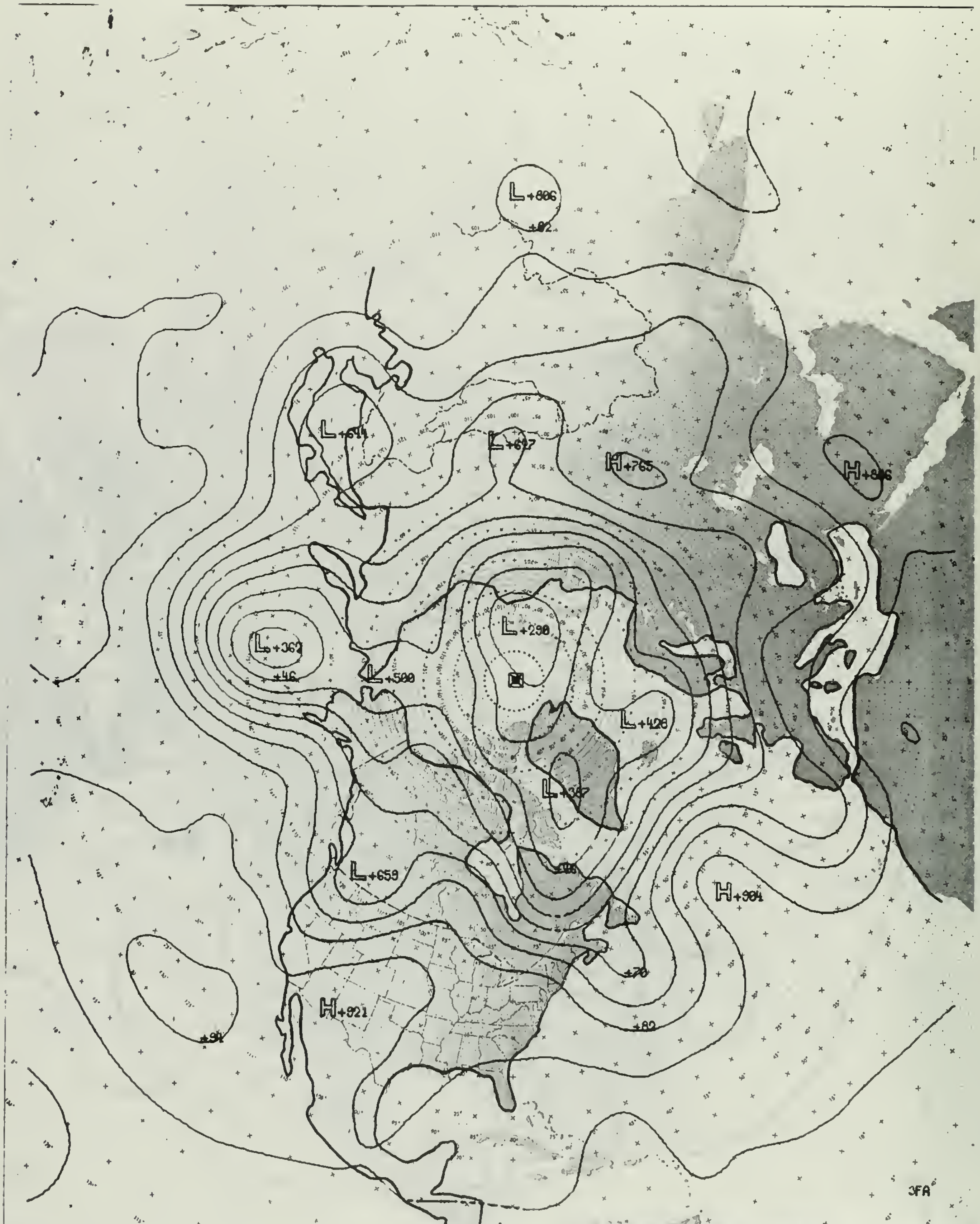

Figure 4.6 500-mb analysis, 4 July 1966

down the European coast and out into the Atlantic west of Gibraltar. Again a trough in Western Russia which extends over the Black Sea and into the Eastern Mediterranean compares favorably. The low over Japan agrees in position but is 20m higher than the verifying height. The trough coming out of Alaska and down Western Canada into the United States does not show a closed low over North America as does the prognostic map but a low of 5659m is indicated on the verifying map and could possibly have been drawn as a closed system.

Table 4.3 lists the error fields for the 850-mb level for both summer and winter situations. This table shows a substantial decrease in the error values. Since this model is divergent, it might be expected to perform better at a level where divergence has more effect. It should also be remembered that the gradients are not as strong as at 500mb.

At 850mb there does not seem to be any preference for a particular tuning constant. Figures 4.7, 4.8, and 4.9 are 24-hour forecasts made from 10 July 1966 with tuning constants of minus 1, minus 2, and minus 4, respectively. Investigation of these maps will show no significant difference in location of the troughs and ridges or in intensity of the systems. Table 4.3 shows that varying the tuning constant does not appreciably change the RMSE value for any given day.

Figure 4.10 shows a typical prognostic map for 850mb and figure 4.11 is the verifying map. Investigation of these maps will show quite good agreement in both the location and intensity of the major systems.

Test results, error fields, and investigations of the other maps in both summer and winter show similar patterns and substantiate these

B Term out

850 mb

	Winter				Summer			
Tuning Constant	8 Dec		11 Dec		3 July		10 July	
	P	RMSE	P	RMSE	P	RMSE	P	RMSE
1	0'	75'	6'	69'	-2'	48'	1'	48'
-1	0'	69'	6'	68'	-2'	47'	1'	48'
-2	0'	67'	6'	68'	-2'	48'	1'	49'
-4	1'	64'	6'	69'	-2'	49'	1'	49'

Table 4.3 Results of RMSE vs. tuning constant for 850 mb, B term out

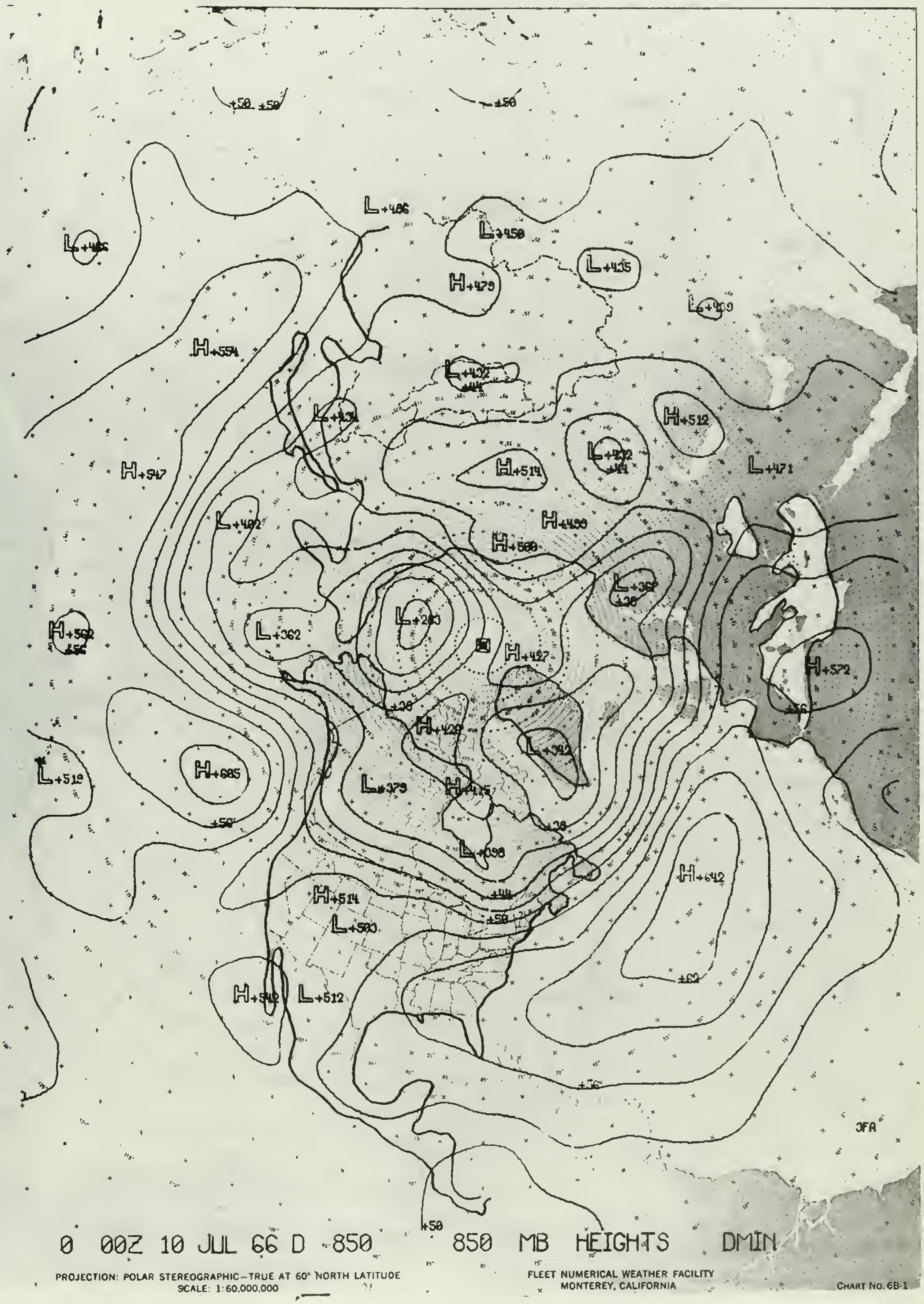

Figure 4.7 24-hour forecast for 850 mb from 10 July 1966, B term out; tuning constant minus 1

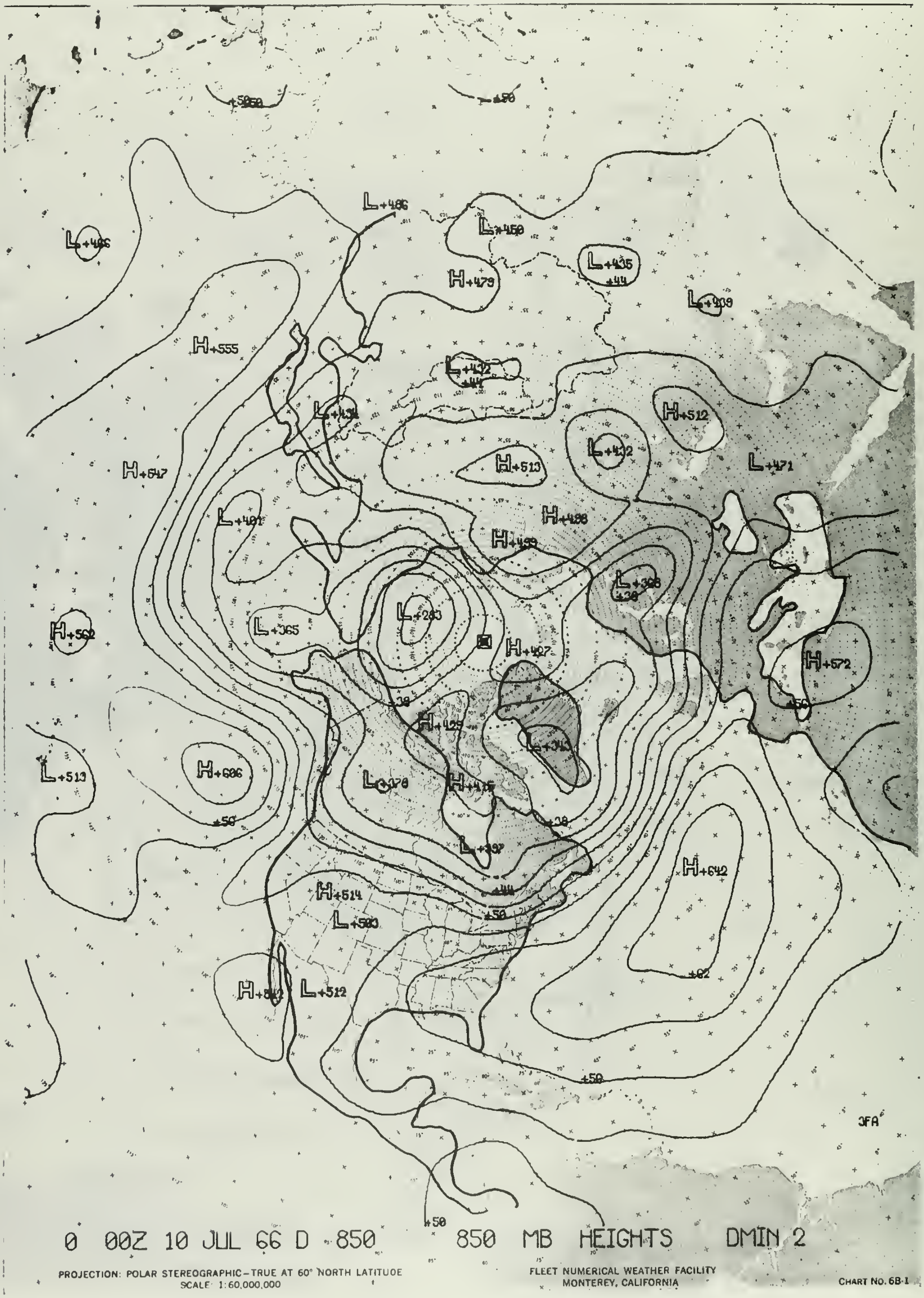

Figure 4.8 24-hour forecast for 850 mb from 10 July 1966, B term out; tuning constant minus 2

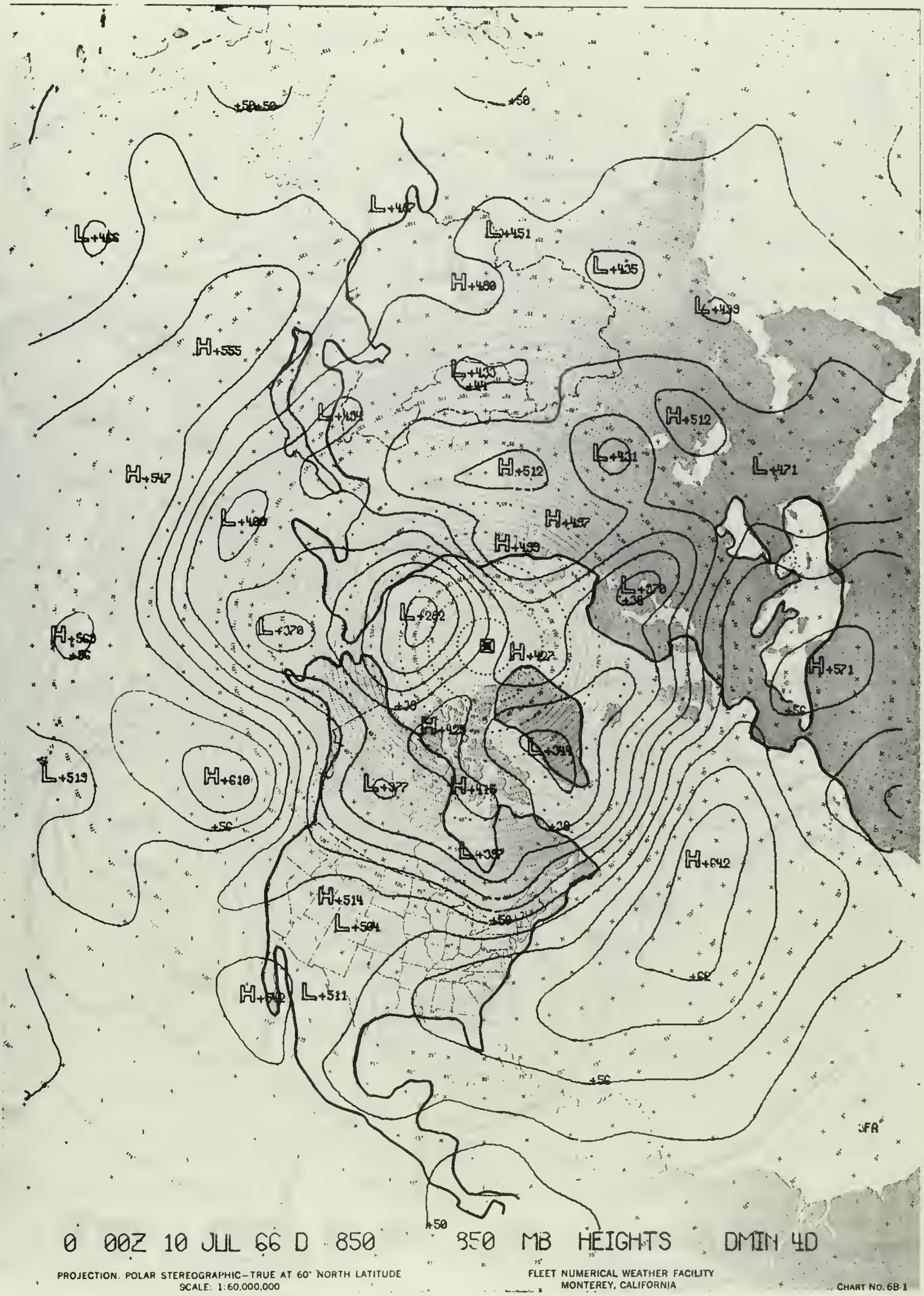

Figure 4.9 24-hour forecast for 850 mb from 10 July 1966, B term out; tuning constant minus 4

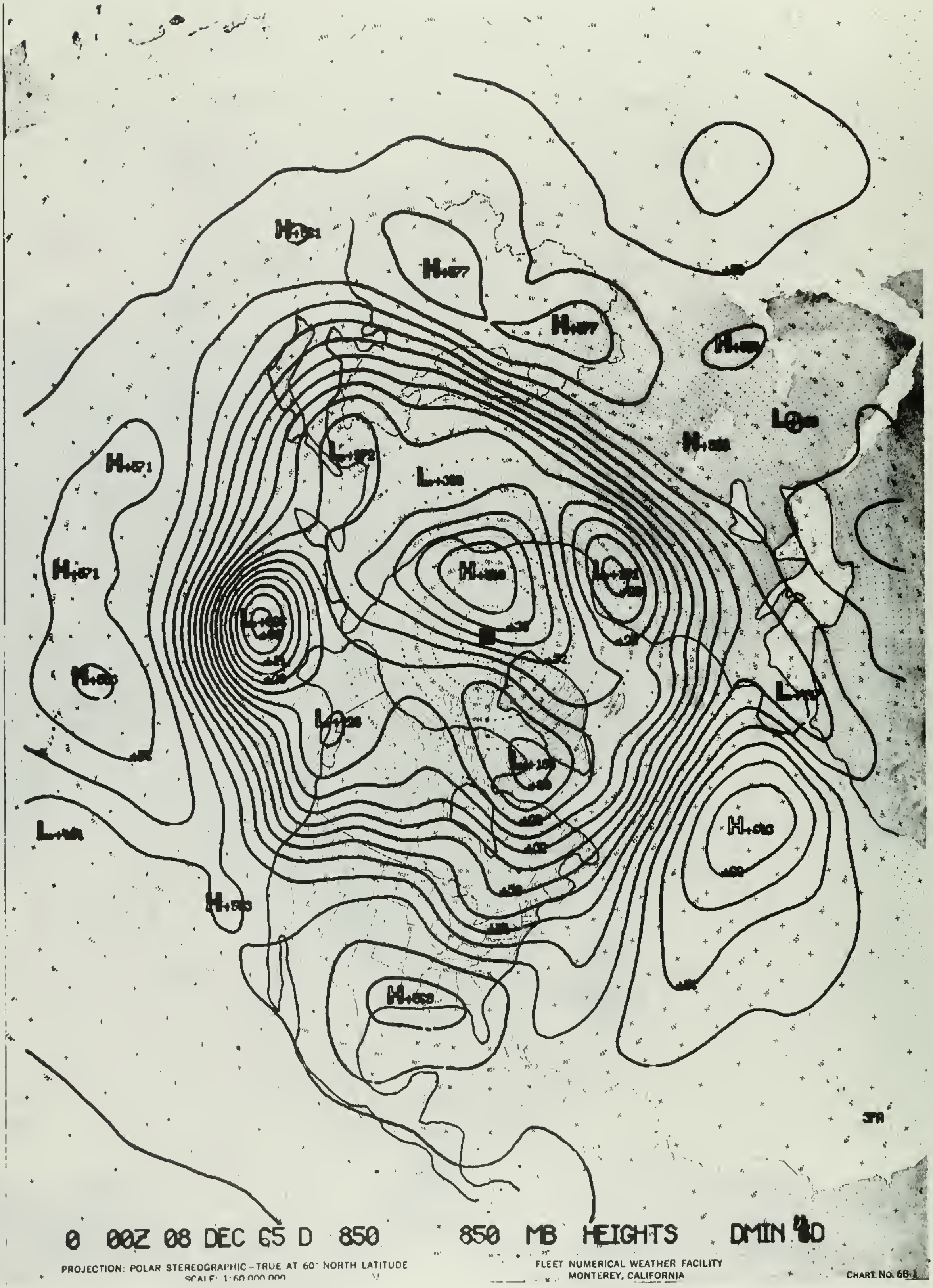

Figure 4.10 24-hour forecast for 850 mb from 8 December 1965, B term out; tuning constant minus 4

Figure 4.11 850-mb analysis, 9 December 1965

initial results.

Table 4.5 is a comparison between the error fields obtained with this model and the error fields of FNWF's model for the same dates at 500 mb. The table shows that this model produces results comparable to those of the present operational model and in most cases might surpass it if this model were used as a first guess field for analysis.

Since FNWF did not have an error field for 850mb, it was necessary to look elsewhere for comparison purposes. In 1962, Nicholson [4] investigated a divergent model proposed by 'Arnason [1]. On the basis of the good results obtained from initial testing, 'Arnason's model was recommended for further investigation. Although an exact comparison is not possible since the days chosen for testing were not the same, it is felt that some benefit can be derived by comparing the order of magnitude of the error fields for each model.

Table 4.6 shows the 850-mb RMSE values for both summer and winter situations. The verification scores for 'Arnason's model are those obtained using the optimum version of the model. The values entered for Duthie's model are those showing the largest errors.

During initial testing at 300 mb, it was found that a relaxation coefficient of 17cm was to small. This coefficient required the computer to make in excess of fifty passes to arrive at a solution. Since each pass takes approximately a second and a half, it required close to one hour to make a 24-hour forecast including printing. It was decided to try 35cm on a trial basis. This cut the running time in half and was used throughout the remaining tests. However it is felt that this coefficient could still be increased and further experimentation is recommended.

Table 4.4 lists the RMSE values for tests run at 300 mb for both summer and winter situations. As was expected, it shows that the errors have increased substantially, being more than double those for 500 mb. This can partially be explained by the large gradients found at this level.

Figure 4.12 is the 24-hour prognostic map from 11 December 1965 with the B term out. Figure 4.13 is the verifying map. Investigation reveals that the model is moving waves too rapidly eastward. Figure 4.14 is the 24-hour prognostic map for the same time but with a tuning constant of minus one on the D term. Comparing figure 4.14 with figure 4.12 shows that the tuning constant has slowed the waves down somewhat but they are still not in agreement with their verifying positions. Analysis of other maps with various tuning constants shows that none was able to compensate for the strong zonal wind at 300 mb. Figure 4.15 is the prognostic map for a summer situation with the B term out and a tuning constant of minus one on the D term. Figure 4.16 is the verifying map. In summer when the zonal wind is not quite as strong, the errors are reduced but the forecast waves are still moving too rapidly.

It is felt that by using the gradient wind instead of the geostrophic wind in the C term of the model, it will reduce the speed of movement. Since the patterns of the prognostic and verifying maps are quite similar this modification should reduce the overall error field.

During the course of this investigation it was found that the use of RMSE to define an error field did not do an adequate job. RMSE is only a measure of the difference in numerical values of two parameters. It

B term out

300 mb

	Winter		Summer	
Tuning Constant	11 Dec 1965 P	RMSE	3 July 1966 P	RMSE
1	32'	509'	28'	223'
-1	1'	450'	3'	216'
-2	-156'	523'	-12'	222'
-4			-81'	293'

Table 4.4 Results of RMSE vs. tuning constant for 300 mb, B term out

Model vs Fleet Numerical

500 mb

Model	Winter				Summer			
	8 Dec		11 Dec		3 July		10 July	
	P	RMSE	P	RMSE	P	RMSE	P	RMSE
Duthie Model	3'	107'	1'	160'	-3'	81'	0'	72'
FNWF Model	11'	105'	18'	106'	-9'	79'	2'	75'

Table 4.5 RMSE values for FNWF model vs. Duthie model, 500 mb

850 mb

	Winter	Summer
Model	RMSE	RMSE
'Arnason Model	111'	87'
Duthie Model	67'	50'

Table 4.6 RMSE values for 'Arnason model vs. Duthie Model, 850 mb

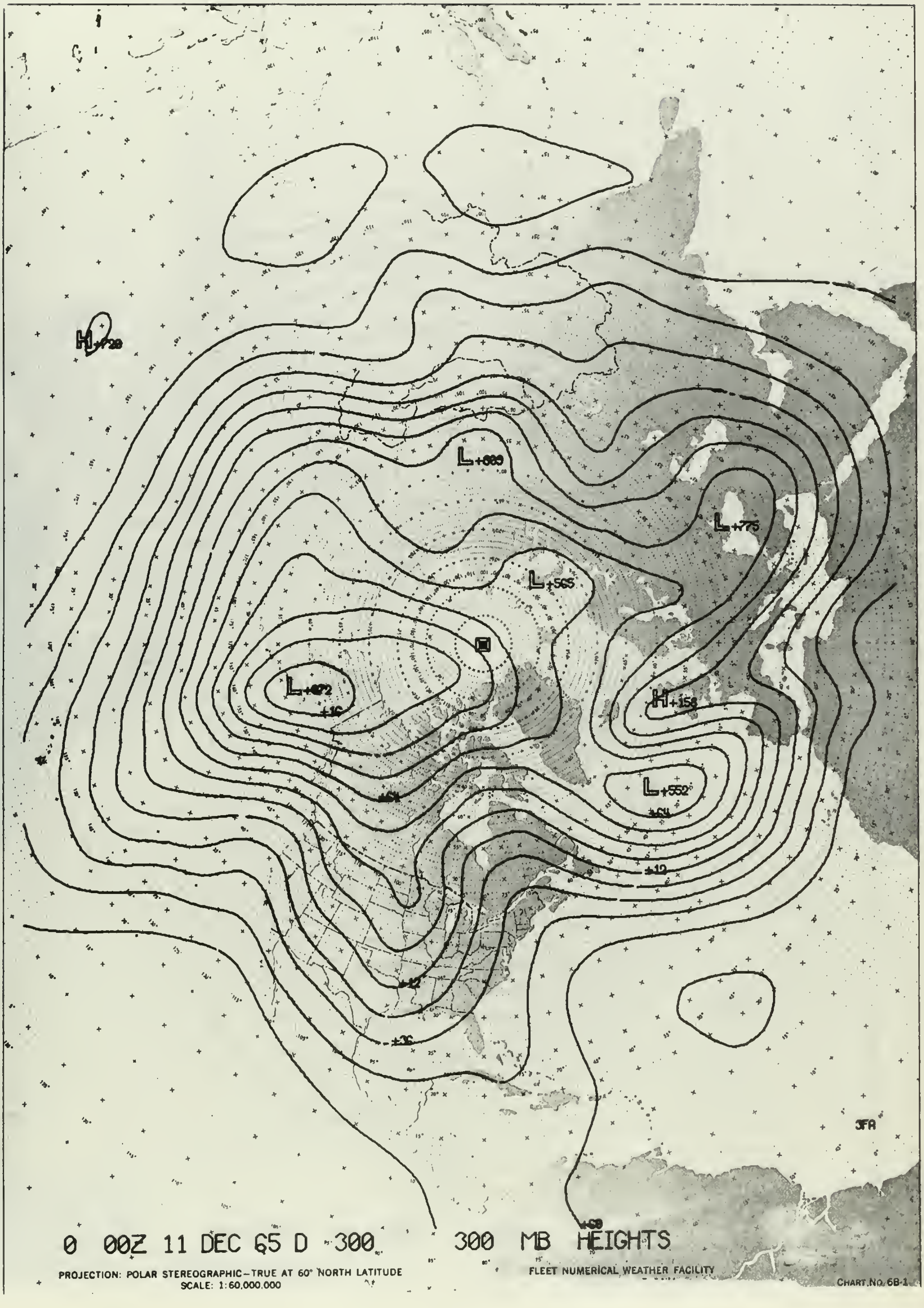

Figure 4.12 24-hour forecast for 300 mb from 11 December 1965, B term out

Figure 4.13 300-mb analysis, 12 December 1965

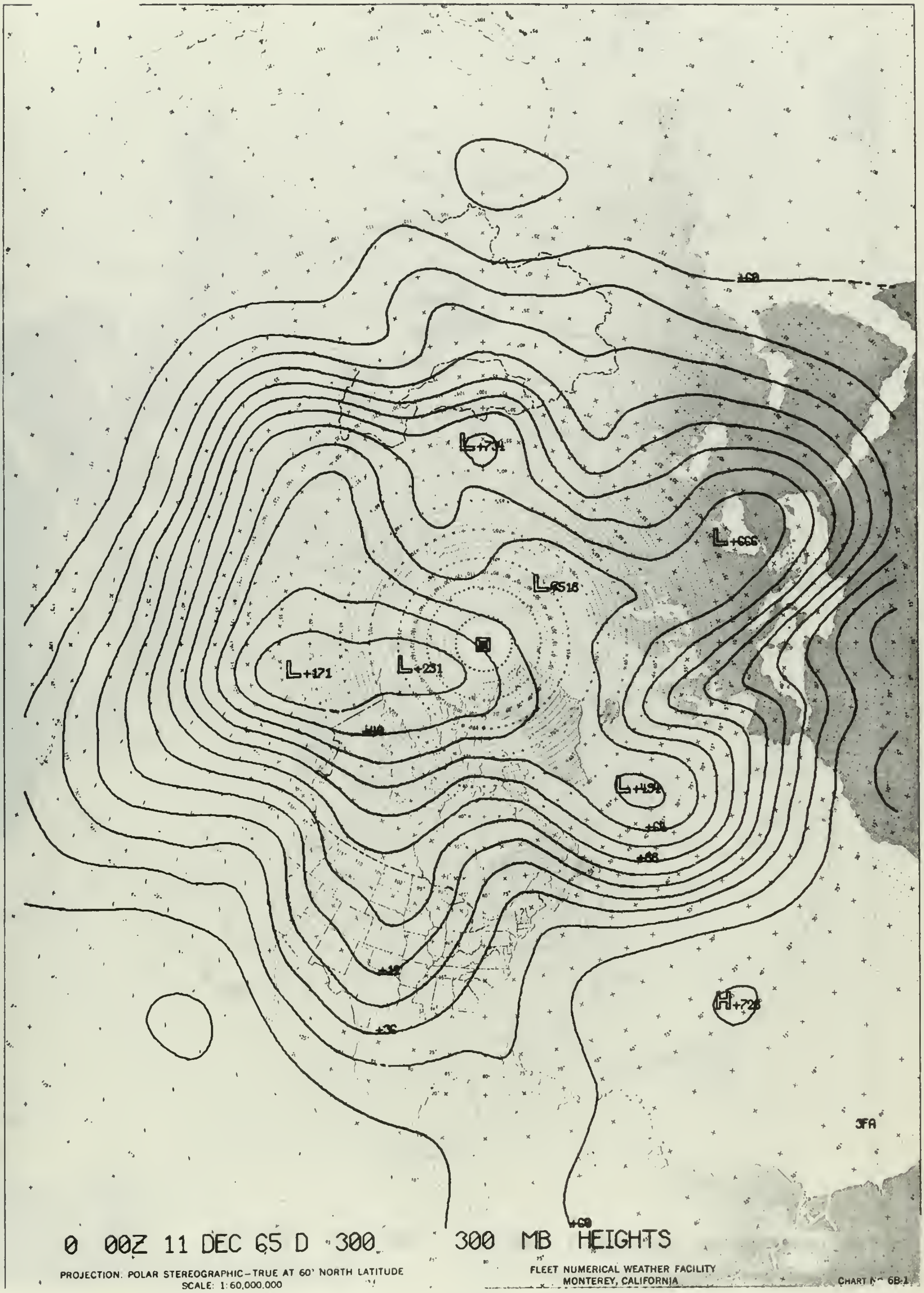

Figure 4.14 24-hour forecast for 300 mb from 11 December 1965, B term out; tuning constant minus 1

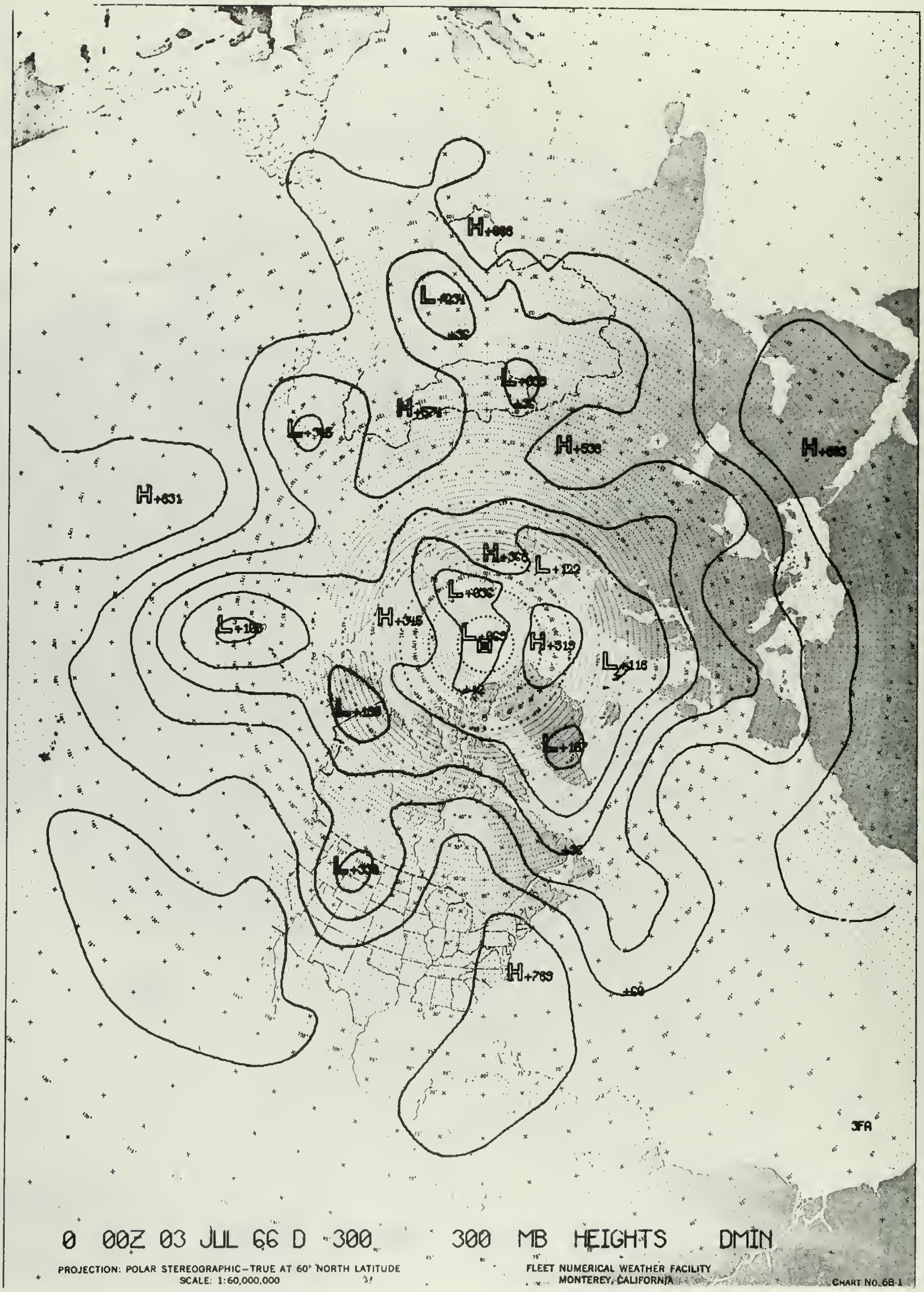

Figure 4.15 24-hour forecast for 300 mb from 3 July 1966, B term out; tuning constant minus 1

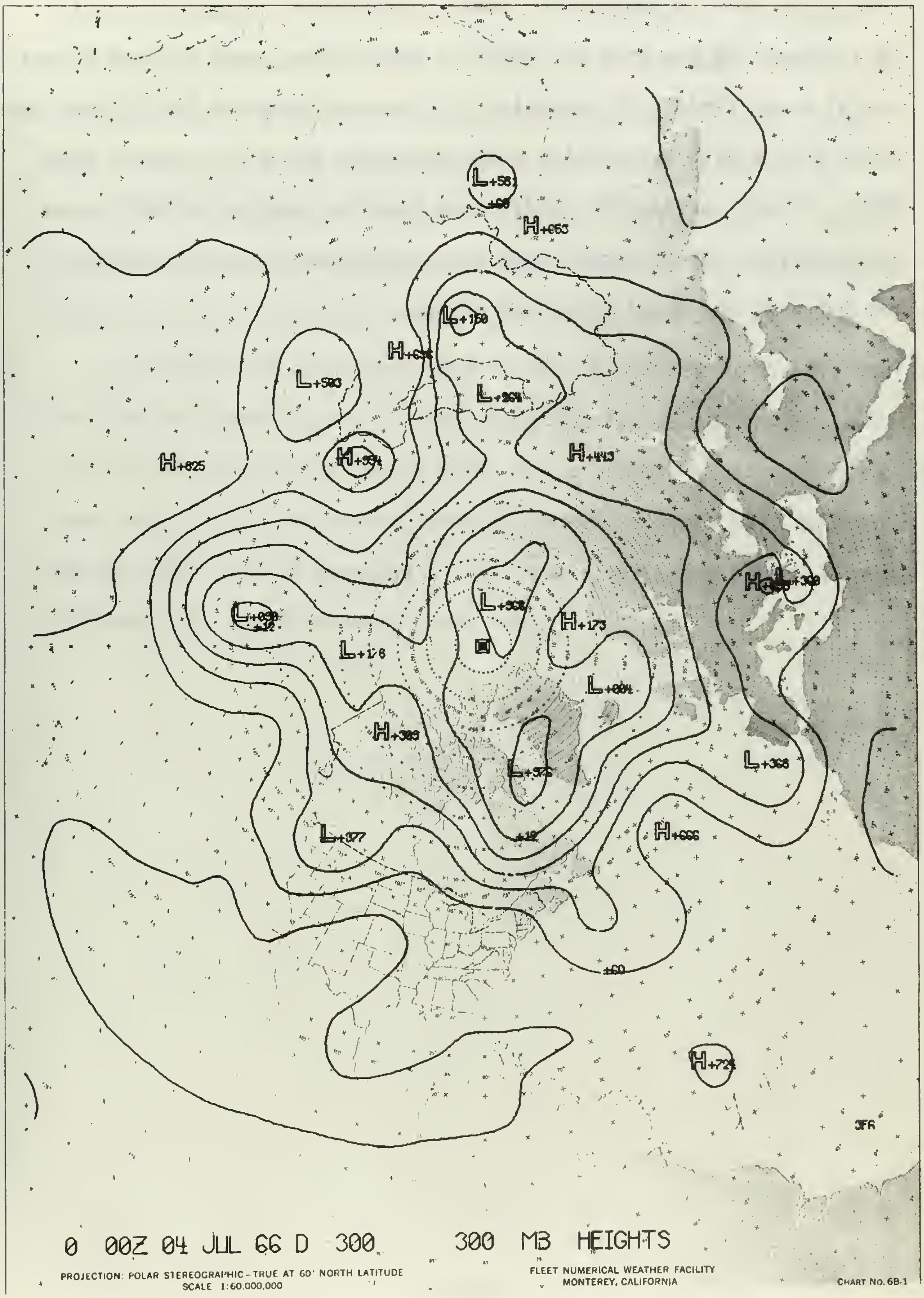

Figure 4.16   300-mb analysis, 4 July 1966

gives no indication as to how the maps resemble each other. It is felt that using RMSE in conjunction with a correlation coefficient, which is a measure of how much the products look alike, would provide a more useful error field. For example, a 300-mb map compared to a 500-mb map would show a high correlation coefficient but would also have a high RMSE. A high correlation coefficient together with a low RMSE would indicate that the prognostic map not only looked like the verifying map but also had small numerical errors.

5. Conclusions.

On the basis of the results of this investigation, the model produces a prognostic map which is a very good representation of the verifying data. At both 500 mb and 850 mb the waves of the 'tuned' model move with a speed consistent with the verifying waves and the location and intensity of the centers agree remarkably well. At 300 mb the model tends to move systems too far. This is due to the use of a geostrophic wind with the strong zonal components at this level.

In view of the close agreement at 500 mb and below, it is felt that further investigation is warranted, incorporating the gradient wind in lieu of the geostrophic wind, the geostrophic relative vorticity (equation 2.6 with the second term in the brackets omitted) and daily testing begun over an extended period to determine the feasibility of this model for possible operational use.

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13. ABSTRACT

A divergent geostrophic prediction model proposed by Duthie is investigated to determine its usefulness in producing realistic forecasts and to determine the feasibility of further research using the gradient wind.

24-hour forecasts were made using the prediction equation,

$$\underset{(A)}{\Delta^2 \frac{\partial z}{\partial t}} - \underset{(B)}{\nabla \frac{\partial z}{\partial t} \cdot \nabla \ln f} = \underset{(C)}{-J(z, \zeta_g)} + \underset{(D)}{\zeta_g J(z, \ln f)}$$

at 300 mb, 500 mb, and 850 mb for summer and winter situations, with and without term B and with a tuning constant on term D.

Tables presenting the error fields for these tests are included, along with the plotted forecast and verifying maps. These tables and illustrations will show that the best results at 500 mb and 300 mb are obtained with the B term out and a tuning constant of minus four and minus one respectively on the D term. At 850 mb different tuning constants produced no significant changes in the prognostic charts.

The results of this investigation show that usable prognostic maps are produced, that the model tested has operational potentiality, and that further testing is warranted.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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